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THE HYDROFOIL CORPORATION

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ANNAPOLIS, MD.

TECHNICAL REPORT No. H-R 6

CONFIDENTIAL

PROPOSED DESIGN AND TEST OF PILOT CHANNEL

PREPARED FOR OFFICE OF NAVAL RESEARCH
Washington, D. C.
Contract Nonr - 13600 (1, 2, 3, 4)

February 1951

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February 1, 1951

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by

E. Rottmayer

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SUMMARY

A water channel suitable for the study of hydrofoils is discussed. It is demonstrated that in the interest of economy a pilot channel should be considered first.

The basis for the design of such a pilot channel is given. The factors considered were; test section size, approach contour, control of rate of flow, and pump and motor size required. A method of construction is presented that will permit the geometry to be altered at a minimum of expense.

A test program is outlined that will produce design information necessary to construct a large water channel suitable for the study of hydrofoils.

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THE HYDROFOIL CORPORATION

TECHNICAL REPORT HR - 6 February 1, 1951

Subject: Proposed Design and Test of Pilot Channel

Prepared For: Office of Naval Research, Washington, D. C.
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By: E. Rottmayer

References:

(a) Drawings
HD - 1015
HD - 1016.

(b) The Hydrodynamics of the Free Surface Water Tunnel
J. P. O'Neill, California
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(c) Hydrodynamic Research Facilities in the U. S.
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(e) Hydrodynamics - H. Lamb.

1. Introduction

There are many questions regarding both the fundemental theory and the technical applications of hydrofoils that cannot be conveniently investigated except by a water channel. From a technical standpoint, a channel suitable for this type of investigation should be free of surface waves, have a uniform velocity distribution throughout the test section, and a velocity range capable of duplicating the Froude number range anticipated for the practical application. It is also desirable to keep the initial and operational costs as low as possible. There do not appear to be any channels (See Ref. c.) that meet these requirements, and therefore, it was decided to investigate the design of such a channel.

A short study of the problem revealed two important facts. First, the optimum design features will probably have to be determined experimentally and perhaps involve many modifications. Second, the channel must be quite large. In view of these facts, it is apparent that a direct approach would be very expensive and time consuming. It was decided, instead to build a pilot channel from which the optimum design features could be determined quickly and inexpensively. Presented, herein, is the design of such a pilot channel and the associated test program.

2. Test Section Size:

The need for a pilot channel cannot be fully appreciated until the magnitude of the problem is clearly defined. The order of magnitude can be obtained by considering the size of the test section, since the other features will be proportional to it. This section contains a brief discussion of the primary factors that determine the size of the full scale channel.

One factor influencing the size of the test section is the anticipated operating region of the technical application. i. e. the size and velocity of hydrofoils that are of principal interest. It was assumed that the maximum chord should be 15 ft. and the maximum velocity 50 ft/sec. The corresponding operating region can be conveniently illustrated by the means of the Dynamic Similitude Chart described in Ref. b.

A similar chart has been prepared, covering the appropriate range for this application, and appears as Fig. 1. In preparing the chart the properties of water at 60° F were used. The chord of the hydrofoil was selected as the characteristic length in computing the Froude number F_c, Reynolds number R, and Webers number W.

It is apparent that once the chord and velocity are given that F_c, R, and W may be immediately determined. It is also apparent that the operating region is the entire region below line ABC, if the maximum size and velocity assumed above are the criteria.

Inspection of Fig. 1 shows that it is not possible to keep F_c, R, and W the same for model and the prototype. For the purposes of comparing the results with theory or interpreting them for practical design, it is most important that the Froude numbers be the same. The discrepancies in Reynolds and Webers number can be minumized by using as large a model as possible.

The maximum velocity and the depth of the test section are interrelated. The velocity should be small enough that the finite depth of the channel will not appreciably influence the test results. It was assumed that the maximum velocity should be that corresponding to the velocity of a gravity wave with a wave length equal to the depth of the channel. This establishes the maximum Froude number F_h to be equal to 0.4, since:

$$F_h = \frac{V}{\sqrt{gh}}$$

$$V = \sqrt{\frac{g\lambda}{2\pi}}$$

$$\lambda \cong h \quad \text{(condition assumed for maximum velocity)}$$

$$F_h = \sqrt{\frac{1}{2\pi}} = 0.4$$

The optimum depth of the channel was found to be 4 ft. This is a compromise between cost of construction and operation, and test requirements. On the one hand, the depth should be a minimum from the viewpoint of expense, but, on the other hand, it should be large enough to include a reasonably large part of the anticipated test region. The depth selected above can be defended with the use of Fig. 1. On this figure the line EF represents the maximum velocity ($F_h = 0.4$) permissible for a channel of this depth. In order to duplicate the Froude number, F_c, associated with the operating condition B, a model with a chord of .12 ft. must be used. If the depth were decreased an even smaller model must be used. It is not practical to consider a smaller chord, hence, 4 ft. is the minimum depth that should be contemplated. It is interesting to note that if a chord of .5 ft. were used, the depth would have to be increased to 16 ft. to maintain the same Froude number. This, of course, would magnify the construction and operating costs many times, since all dimensions must be increased by the same proportion.

The length of the test section should be 18 ft. This distance was determined in two parts, in the following manner:

The first part is to enable two hydrofoils to be tested in tandem, with a spacing of half a wave length. Since the maximum wave length is to be equal to the depth of the channel, the space required is 2 ft.

The second part is to insure that the flow around the foil is not disturbed by obstructions downstream from the foil. A distance of four wave lengths (16 ft) is required for this purpose.

The width of the test section should be 6 ft. This is to insure that in the tests of foils with finite span, the waves formed at the tip will not be disturbed by the opposite wall within a distance of three wave lengths downstream of the foil. It is expected that the maximum finite span will be 2 ft. The angle which the tip wave formation makes with the axis of the channel is approximately 19° see Ref. <u>e.</u> Hence, the width required is:

$$2 + (3)(4) \tan 19^\circ = 6 \text{ ft.}$$

The anticipated size of the full scale water channel is, therefore, 4 feet deep, 6 feet wide, and 18 feet long. A convenient size for the pilot channel is one-sixth this size. It will then have a test section 8 inches deep, 12 inches wide, and 36 inches long.

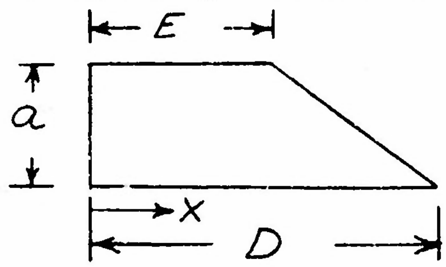
3. <u>Pilot Channel Calculations:</u>

The size of the test section influences the design of the remainder of the channel. The other elements comprising the channel are; plenum chamber, approach, weir, reservoir, and return. Each of these elements will be discussed in this section. It should be pointed out that the dimensions used are not considered to be ideal but will themselves be subject to investigation. In general they were made as large as considered practical with the intention of reducing them as much as possible by experimental investigation.

The size of the plenum chamber depends upon the velocity (or area) ratio, R, between the plenum chamber and the test section, and the length required to control turbulence and velocity distribution. A ratio, R, of 8 was selected. Since the test section, cross-section area is 96 sq. in., the area of the plenum chamber must be 768 sq. in. Although it would be desirable in many ways to vary only the width or the depth, this was not done since the resulting dimensions were excessive. A compromise of 24 inches deep and 32 inches wide was finally used. The length required to control the flow was estimated to be 24 inches.

The approach must connect the plenum chamber to the test section in such a manner as to keep the surface waves to a minimum. No adequate procedure is available to determine in advance the cross-sectional area distribution required to produce this result. It appears reasonable to assume that the disturbance to the surface would be worse where the acceleration and velocity of the fluid were large.

Therefore, it was decided to design the approach so that the acceleration is large where the velocity is small and so that the acceleration approaches zero as the velocity approaches the maximum velocity. This may be accomplished by defining the flow in terms of the acceleration diagram as sketched below.



D = length of approach

a = acceleration

$V = V_p$ (Velocity at entrance) @ $X = 0$

$V = V_t$ (Velocity at exit) @ $X = D$

The required distribution of cross-sectional area was found as follows. It was assumed that the velocity was a function only of the distance, X, along the approach. Then the acceleration is given by:-

$$a = V \frac{dV}{dX}$$

The velocity distribution satisfying the acceleration diagram can be readily obtained. From this the acquired areas are found by the application of the requirement of continuity. The final results are:

$$\left(\frac{A_p}{A_x}\right)^2 = \frac{2(R-1)}{E+D} X + 1 \qquad 0 \le x \le E$$

$$\left(\frac{A_p}{A_x}\right)^2 = \frac{R^2 - 1}{E^2 - D^2} (X-D)^2 + R^2 \qquad E \le x \le D$$

Where A_p = cross-sectional area at the entrance

$R = V_t / V_p = \frac{A_p}{A_t}$

These equations were solved for several cases and the results are given in table 1. From the previous discussion of the plenum chamber R and A_p are already established as 8 and 768 sq. in. respectively. A length D of 60 inches was chosen as being the practical maximum. These cases were calculated using different values of E, namely, 0, 30, and 60 inches.

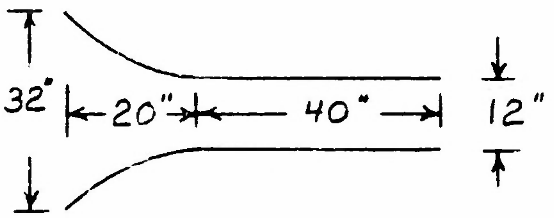
The width of the approach must be 32 inches at the entrance and 12 inches at the exit. In the interest of simplicity of construction and of smooth flow, it is desirable to keep the width constant for as great a length as possible. A 12 inch width may be maintained for the last 40 inches, since most of the change in cross-sectional area occurs in the first 20 inches, note table 1.

A curve, quadratic in form, was fitted to the initial portion of the approach. The resulting equation for the width, W, was;

$$W = \frac{x^2}{20} - 2x + 32 \qquad 0 \leq x \leq 20$$

$$W = 12 \qquad 20 \leq x \leq 60$$

The width distribution is sketched below.



The depth, h, at any station, can now be found by simply dividing the area required by the width. This was done for the three different area distributions previously calculated. Unfortunately very steep slopes were required at the entrance and also a reversed curvature, i.e. a hump near the entrance. Fortunately, this was confined to the initial 20 inches of the approach. Since this region violates the assumption that the velocity is only a function of the distance along the approach, rather seriously this portion was modified by using a smooth curve. Two cases were calculated and are given below.

$$\text{For} \quad E = 0 \quad h = .022975x^2 - 1.1265x + 24$$

$$E = 60 \quad h = .009575x^2 - .709x + 24$$

The accelerations are altered in this region and were calculated from;

$$V = \frac{V_p A_p}{A}$$

$$a = V \frac{dV}{dx} = - \frac{V_p^2 A_p^2}{A_x^3} \frac{dA_x}{dx}$$

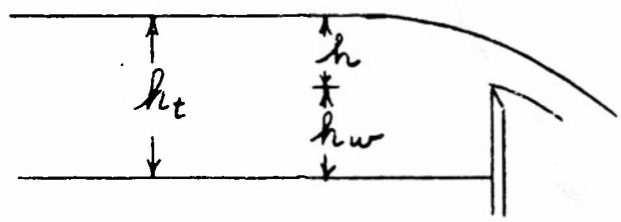
The final results are shown in Fig. 2. On this figure are shown the depth distribution and the associated acceleration diagram.

The weir is required to control the depth of flow in the test section. Its characteristics were calculated and the results are given by Fig. 3. This figure shows both the quantity of flow and velocity as a function of the depth of flow in the test section with the highth of the weir as a parameter.

Their are many weir formulas presented in the literature on this subject. The "King Formula", Ref. d, was used in these calculations since it is an empirical equation based upon the results of several experimental investigators.

Q = Quantity of Flow

W = Width of Channel



Using the nomenclature given above, the King Formula may be written,-

$$Q = 3.34\, W\, h^{1.47} \left[1 + 0.56 \frac{h}{h_t} \right]$$

In these calculations, the width was one foot. Therefore, the average velocity in the test section becomes,-

$$V_t = \frac{Q}{h_t}$$

Also shown in Fig. 3 are V_{cr} and Q_{cr}, which are the velocity and quantity of flow corresponding to a gravity surface wave of length equal to the depth of the channel. These were calculated from the following equations.-

$$V_{cr} = \sqrt{\frac{g\ h_t}{2\ \pi}} = 2.26\ \sqrt{h_t}$$

$$Q_{cr} = V_{cr} \times h_t = 2.26\ h_t^{3/2}$$

The reservoir should be large enough to prevent excessive fluctuations in the level of the water in the reservoir, for the range of velocities contemplated. In the extreme case, the level should not get so low as to suck air into the flow. A reservoir the size of the plenum chamber (24" x 24" x 32") should prove satisfactory. This will make the change in level in the reservoir about twice the change in level in the plenum chamber, a change in depth of a few inches.

The return is about 12 ft. long and must include a throttling valve and a pump and motor. The valve is necessary to control the quantity of flow in the test section. A centrifugal pump capable of delivering 600 g.p.m. against a head of 20 ft. should prove satisfactory.

To make certain that the pump cannot overload the motor, a 5 horsepower electric motor should be installed.

The size of the pump was estimated in the following manner. First the critical quantity of flow, i.e. $F_h = 0.4$ and $h_t = 8$ in., was calculated and found to be approximately 550 g.p.m. Then the head losses were determined for several pipe sizes. There may be considerable error, since most of the losses are due to entrance, exit, elbows, and discontinuities, all of which are difficult to find exactly. For a six inch diameter pipe, a total head of about 3 ft. was found. Therefore, a pump selected above should not only meet the design conditions, but should be capable of providing flows considerably in excess of the design conditions. This is particularly desirable so that the maximum velocity for which smooth flow occurs may be investigated.

4. Pilot Channel Design:

It is important that the pilot channel be easy to modify, since, the purpose of the pilot channel is to obtain design information for a full scale channel by experimental means.

For this reason wood is used in the construction wherever possible. Further, the method of construction permits changes to be made to the depth distribution in the approach, the slope of the test section bottom, and the length of the approach and test section with little difficulty. The general features of the design are shown schematically in Fig. 4.

The framework consists of heavy wooden members, see Ref. a. To this are attached the plenum chamber and the side walls of the approach and test section. The reservoir is a box complete in itself, so that it may be moved if a shorter channel is desired.

The side walls are made of Philippine mahogoney plywood because it can be easily finished to a smooth surface. Attachment screws are countersunk and plugs used to preserve the smooth surface. Horizontal reference lines are drawn the entire length of the test section with a vertical spacing of one-half inch. The surface is painted a color that will contrast well with the water surface.

The bottom of the approach and test section consists of two parts and they are not integral with the side walls. The bottom of the test section is flat and smooth. It is made to fit the side walls snugly and is supported in such a manner that its slope may be changed. The bottom of the approach consists of a framework built up to the proper contour and covered by plywood. It also fits the side walls snugly and is supported by the framework. The small gap between the side walls and the bottom is sealed by a suitable filler.

The weir is simply a rectangular plate with a sharp edge on the top. Provision is made for adjusting the highth of the weir.

The return contains a valve, pump, and motor. A centrifugal pump with a capacity of 600 g.p.m. at a head of 20 ft. is used. A splash proof 5 horsepower electric motor is employed to drive the pump.

5. Test Program:

The entire test program cannot be specified in advance due to the nature of the tests. At best, only the initial series of tests can be specified now, and a general outline given for the remaining tests.

The first group of tests will be with the bottom of the test section horizontal and an approach bottom of type E = 0 mod., see Fig. 2. Several rates of flow will be investigated for several depths of the flow in the test section. Velocity distribution will be obtained in the plenum chamber and the test section for each run. In addition surface waves will be observed visually. In each instance the maximum velocity at which surface disturbances become serious will be given special attention.

After this an attempt will be made to improve the character of the flow by the use of resistances, such as screens, in the flow. Then the effect of the slope of the test section bottom will be studied. The best arrangement in regard to both velocity distribution and surface disturbances will be determined.

The next step will depend upon the results already obtained. If the flow is not satisfactory, probably the approach bottom will be modified until good flow characteristics are obtained. If this is not successful the width distribution may be changed.

After a good flow has been obtained, consideration will be given to making the channel shorter. The channel will be made as short as possible, and the above procedure repeated in an effort to again obtain good flow characteristics.

E. Rottmayer

E. Rottmayer

TABLE I

CROSS - SECTIONAL AREAS REQUIRED IN THE APPROACH

STA.	AREA - SQ. IN.	
	E = 60	E = 0
0	768	768
5	307.2	231.0
10	226.5	170.7
15	187.8	143.7
20	163.7	128.0
25	146.1	117.8
30	134.7	110.6
35	125.0	105.4
40	117.1	101.7
45	111.7	99.1
50	105.0	97.3
55	100.2	96.3
60	96.0	96.0

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TABLE NO. I	HR - 6

SIMILITUDE CHART

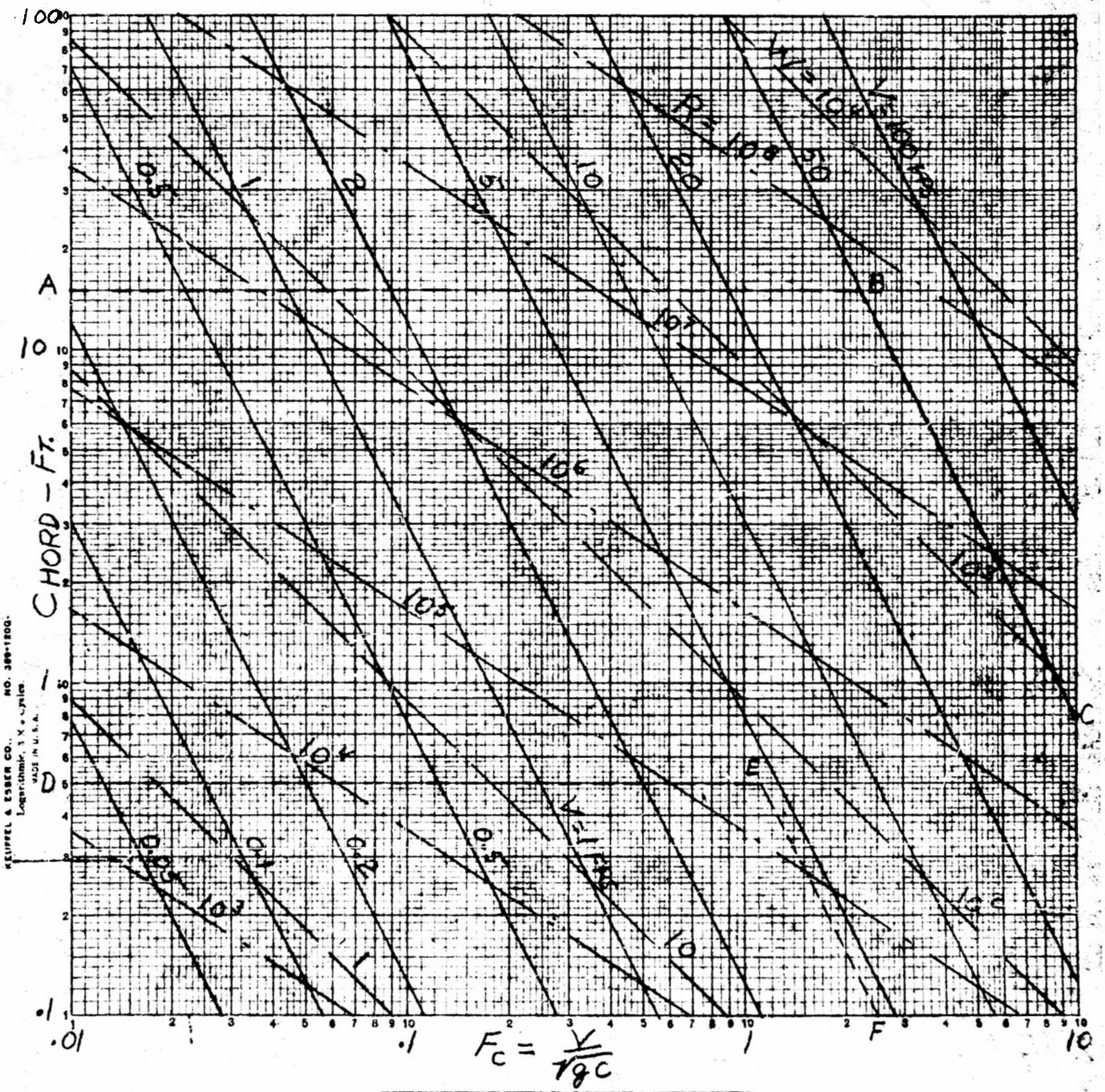

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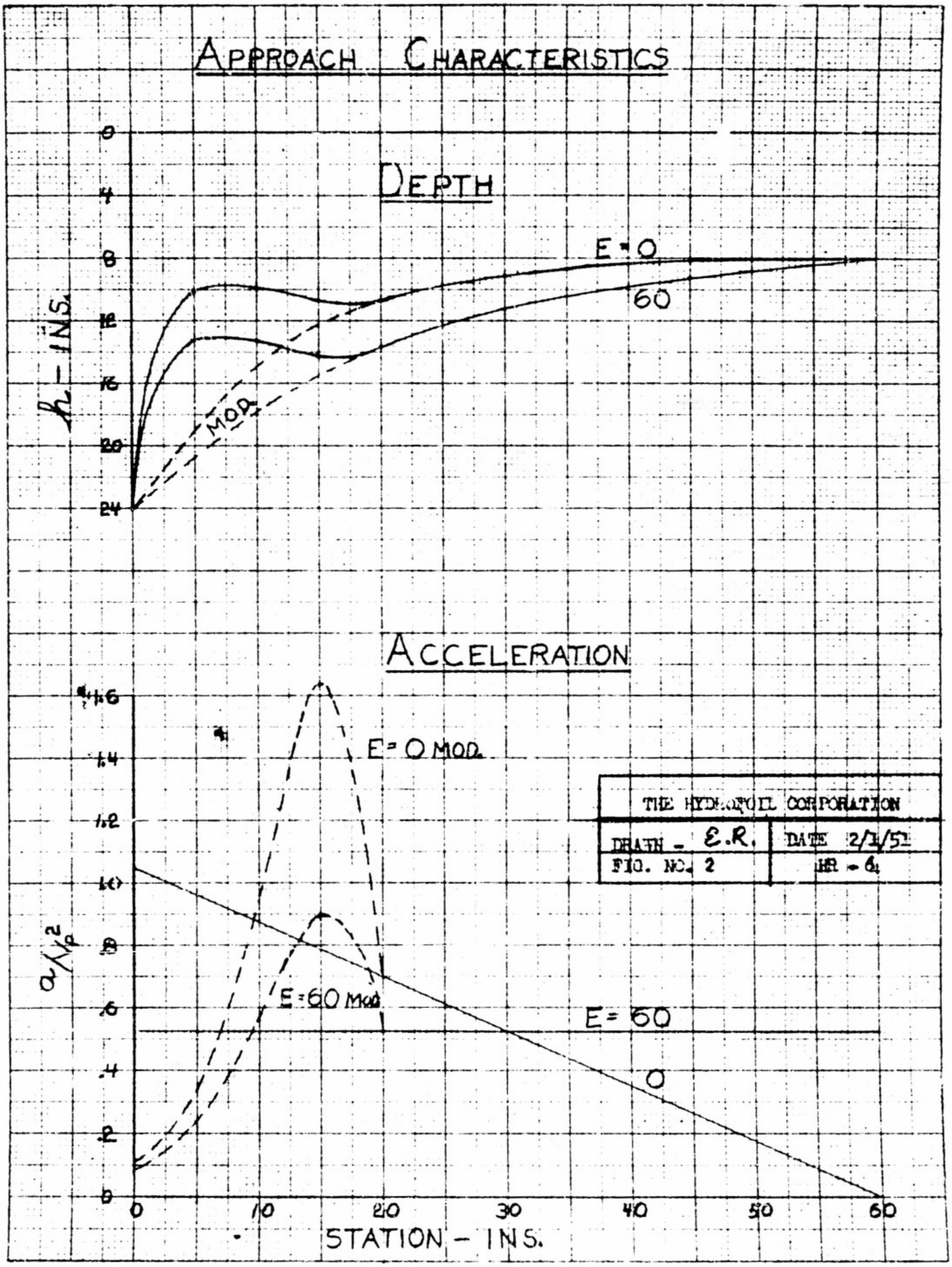
FIG. NO. 1	HR - 5


APPROACH CHARACTERISTICS
DEPTH
h - INS.
0
4
8
12
16
20
24
E = 0
60
MOD.
ACCELERATION
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
E = 0 MOD.
E = 60 MOD.
E = 60
0
0
10
20
30
40
50
60
STATION - INS.
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DATE 2/1/51
FIG. NO. 2
HR - 6

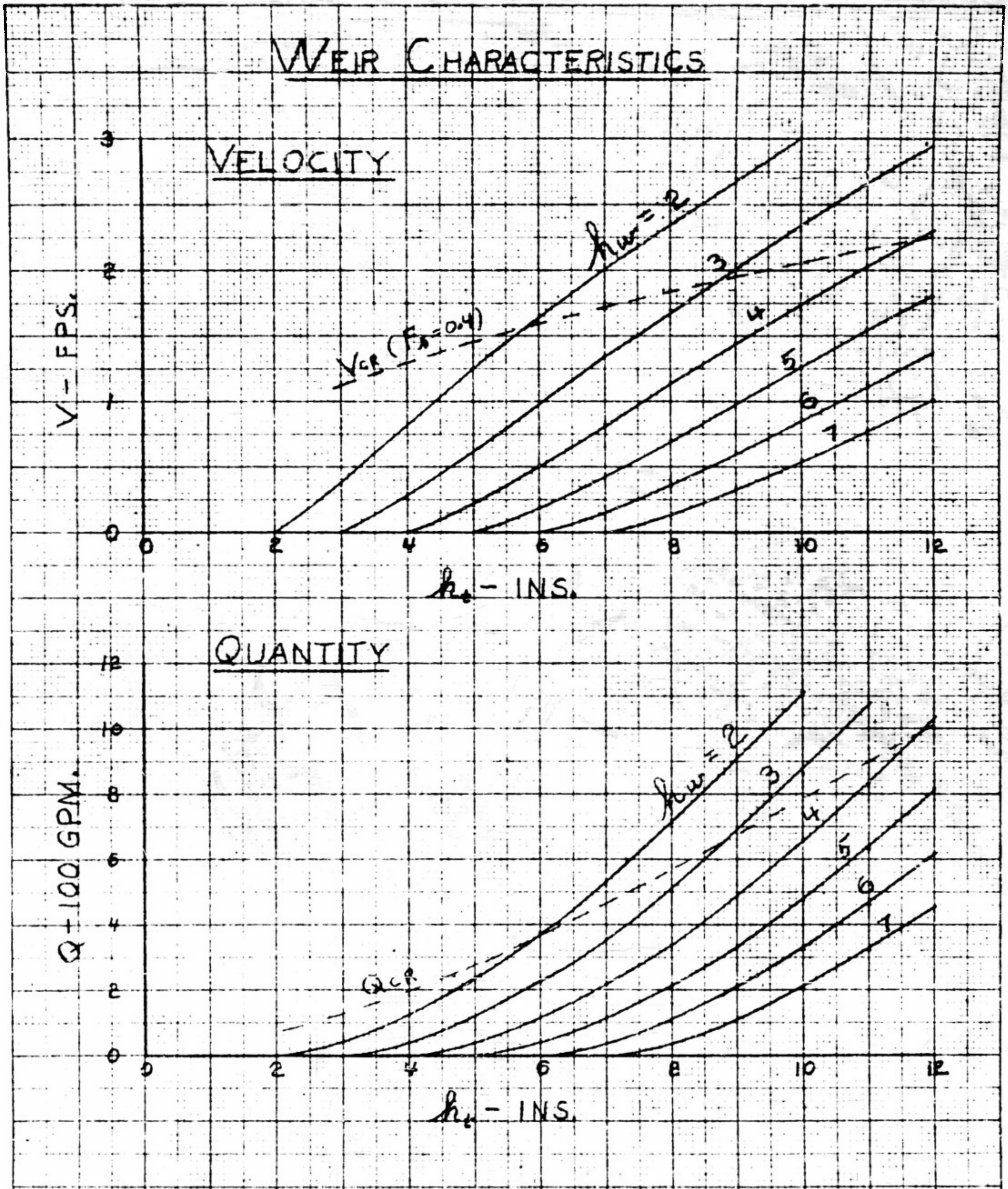

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FIG. NO. 3	HR - 6

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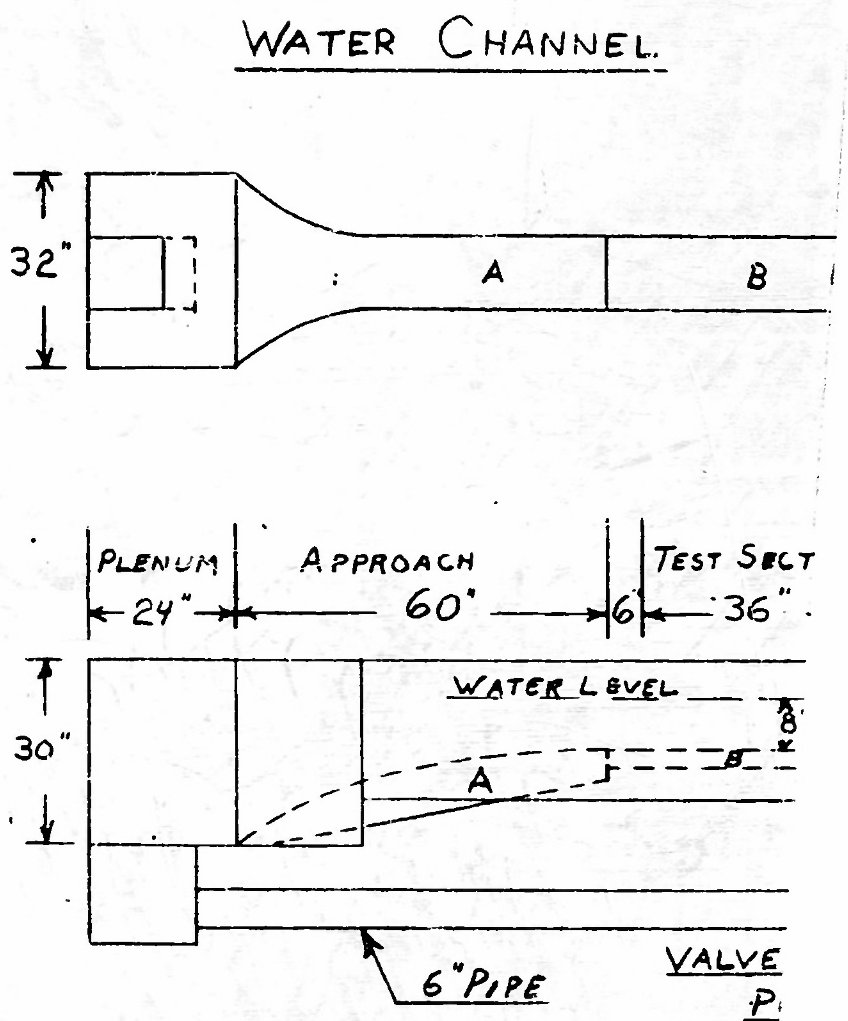

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DRAWN - E.R.	DATE 8/1/51
FIG. NO. 4	HR - 6